

LIGHTWEIGHT, FLEXIBLE SOLAR CELLS ON STAINLESS STEEL FOIL AND POLYMER FOR SPACE AND STRATOSPHERIC APPLICATIONS

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INTRODUCTION

The availability of low-cost, lightweight and reliable photovoltaic (PV) modules is an important component in reducing the cost of satellites and spacecraft. In addition, future high-power spacecraft will require lightweight PV arrays with reduced stowage volume. In terms of the requirements for low mass, reduced stowage volume, and the harsh space environment, thin film amorphous silicon (a-Si) alloy cells have several advantages over other material technologies (1). The deposition process is relatively simple, inexpensive, and applicable to large area, lightweight, flexible substrates. The temperature coefficient has been found to be between -0.2 and -0.3 %/°C for high-efficiency triple-junction a-Si alloy cells, which is superior for high temperature operation compared to crystalline Si and triple-junction GaAs/InGaP/Ge devices at -0.53 %/°C and -0.45 %/°C, respectively (2). As a result, the reduction in efficiency at high temperature typical in space conditions is less for a-Si alloy cells than for their crystalline counterparts. Additionally, the a-Si alloy cells are relatively insensitive to electron and proton bombardment. We have shown that defects that are created by electrons with energies between 0.2 to 2 MeV with fluence up to 1×10^{15} e/cm² and by protons with energy in the range 0.3 MeV to 5 MeV with fluence up to 1×10^{13} p/cm² can be annealed out at 70 °C in less than 50 hours (1). Further, modules incorporating United Solar's a-Si alloy cells have been tested on the MIR space station for 19 months with only minimal degradation (3).

For stratospheric applications, such as the high altitude airship, the required PV arrays are typically of considerably higher power than current space arrays. Airships typically have a large area available for the PV, but weight is of critical importance. As a result, low cost and high specific power (W/kg) are key factors for airship PV arrays. Again, thin-film a-Si alloy solar cell technology is well suited to such applications.

United Solar Ovonic Corporation (United Solar), in collaboration with space companies and government laboratories, has been working on optimization of a-Si alloy solar cells for space and stratospheric applications for a number of years. United Solar has leveraged its decades of experience in providing a-Si alloy solar cells to the terrestrial market to develop products for the space and stratospheric markets. Considerable progress has been made over the last several years in demonstrating the use of a-Si alloy solar cells for space use, including the challenges of optimization of the solar cells to reach high efficiency under the AM0 spectrum and qualification of the cells and modules under the harsh space conditions. The culmination of this work is the transition from R&D demonstrations to the availability in production volumes of a-Si alloy solar cells for space and stratospheric applications. This paper presents an overview of United Solar's approaches, as well as the present status and performance of United Solar's cells made using high-volume roll-to-roll deposition for space and stratospheric application.

CELL STRUCTURE

It is well recognized that a multi-bandgap, multijunction cell structure offers the maximum advantage to obtain high efficiency in a-Si alloy solar cells and modules (1, 4). United Solar's space and stratospheric cells utilize a triple-junction a-Si alloy structure deposited by plasma-enhanced chemical vapor deposition onto

substrates predeposited with a textured silver/zinc oxide (Ag/ZnO) back reflector. The structure is shown in Figure 1. In this structure, the top cell uses an a-Si alloy with an optical gap of ~1.8 eV for the intrinsic (*i*)-layer to capture the blue photons. The *i*-layer for the middle cell is an amorphous silicon-germanium (a-SiGe) alloy with about 10-15% Ge. The optical gap is ~1.6 eV, which is ideally suited for absorbing the green photons. The bottom cell captures the red and infrared photons and uses an *i*-layer of a-SiGe alloy with about 30-40% Ge, corresponding to an optical gap of ~1.4 eV. Light that is not absorbed in the cells is scattered back from the textured back reflector at an oblique angle to facilitate multiple passes. An indium tin oxide (ITO) coating serves as both an antireflection layer and the top carrier collection layer. For the large-area production cells, a wire grid and bus bars are added.

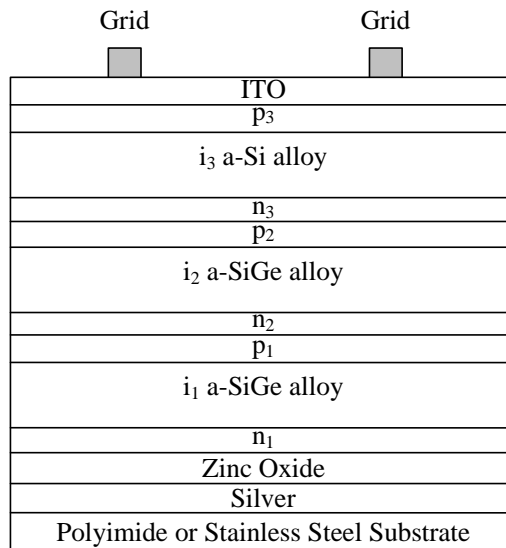


Figure 1. Cross-section of the triple-junction a-Si alloy solar cell.

MANUFACTURING PROCESS

United Solar currently has a manufacturing plant making terrestrial products with an annual capacity of 25 MW (Fig. 2), and is currently constructing the facilities and machines to double that capacity. Since the initial 25 MW/yr production line has been operational, the machines from the previous terrestrial manufacturing line (Fig. 3) with a terrestrial production capacity of 5MW/year have been dedicated to development and manufacture of lightweight cells matched to the AM0 spectrum for space and stratospheric applications. Under a program funded by the Air Force Research Laboratories, we have developed the cell designs and technology to produce lightweight cells on thinned stainless steel or polymer substrates in high volume for space and stratospheric applications.

The manufacturing process for cells on stainless steel substrate consists of the following steps. A roll of stainless steel, half-a mile long, 14" wide and 5 mil thick, moves in a continuous manner in four machines that serve the purpose of i) washing, ii) depositing the back reflector, iii) depositing the a-Si and a-SiGe alloy layers, and iv) depositing the ITO. Following deposition of the ITO, the coated web, which is a half-mile-long solar cell, is first cut into 9.4" x 14" slabs. The slabs are then processed to define cell size, passivated to remove shunts and shorts and tested to ascertain quality. Grid wires and bus bars are next applied. A proprietary coating is then applied to top of the cells using a non-vacuum process. The steel is next thinned from the back to a thickness of 0.5 to 1.0 mil to reduce the mass of the cells. Finally the individual cells are cut from the slabs. The available production cells and their dimensions are listed in Table 1. Figure 4 shows the location of bus bars and the wire grid for a L-cell on stainless steel.

For cells on polymer substrate, the processing sequence is similar. The main differences are as follows. 1) Prior to roll-to-roll deposition of the thin film layers, the polymer is bonded to a roll of steel. 2) The negative bus

bars are located on the front of the cell, underneath the positive bus bars in contact with the back reflector. The ends of the negative bus bars wrap around onto the top of the positive bus bars at one edge of the cell to give accessible negative contact pads. 3) During the steel thinning step, all of the steel is removed from the cell, except for a narrow frame around the edges. This frame is later removed when the cell is cut to final size. Figure 5 shows the location of contacts and the wire grid for the production-size cell on polymer substrate.



Figure 2. The roll-to-roll a-Si deposition machine for terrestrial products with 25 MW/year capacity.



Figure 3. The roll-to-roll a-Si deposition machine previously used for terrestrial products with 5 MW/year capacity, now dedicated to research and production of space cells.

Table 1. Available cell dimensions on stainless steel substrate.

Cell	Overall Dimensions		Aperture Dimensions	
	L	23.88 cm x 35.56 cm	849.1 cm ²	23.68 cm x 34.06 cm
S	11.94 cm x 35.56 cm	424.6 cm ²	11.77 cm x 34.06 cm	400.9 cm ²
F	7.96 cm x 35.56 cm	283.1 cm ²	7.80 cm x 34.06 cm	265.7 cm ²
H	3.98 cm x 35.56 cm	141.5 cm ²	3.83 cm x 34.06 cm	130.4 cm ²

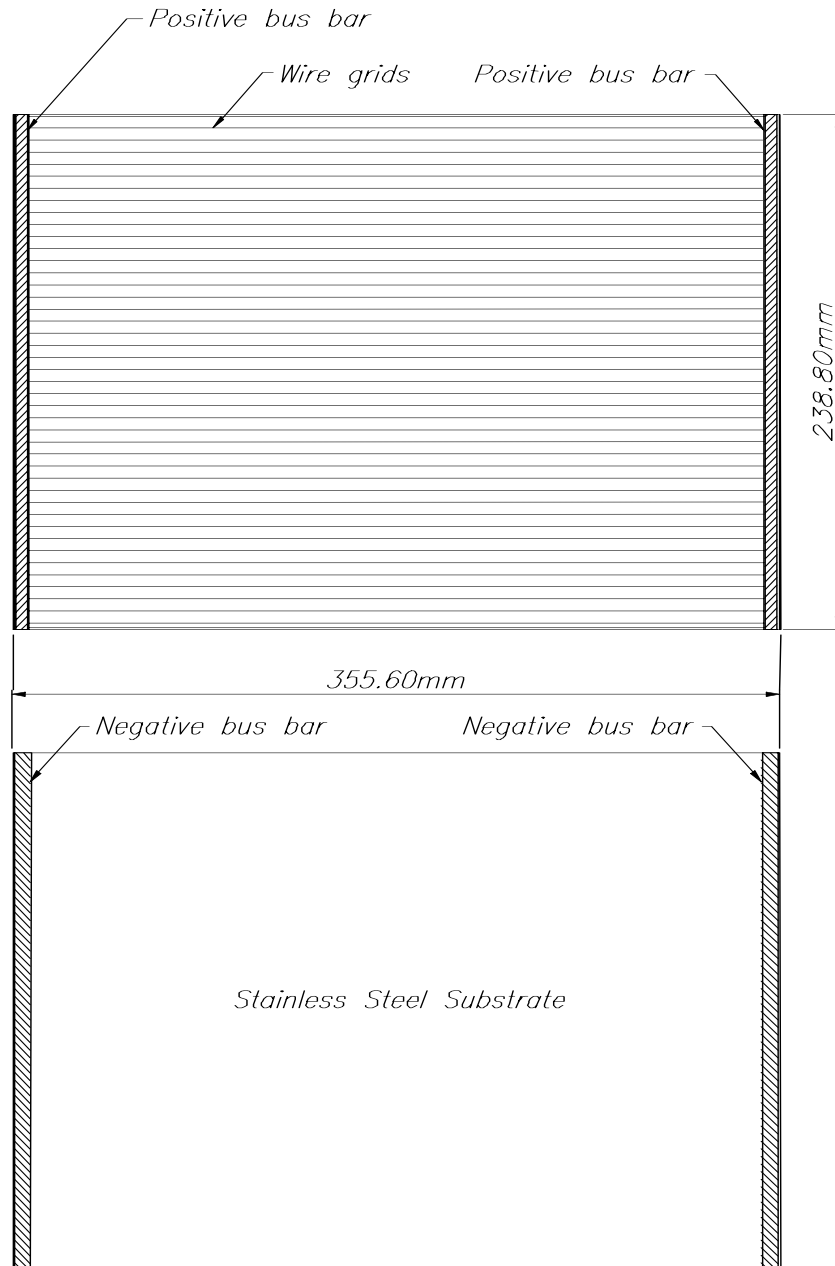


Figure 4. Schematic diagram of the front and back of an L-strip.

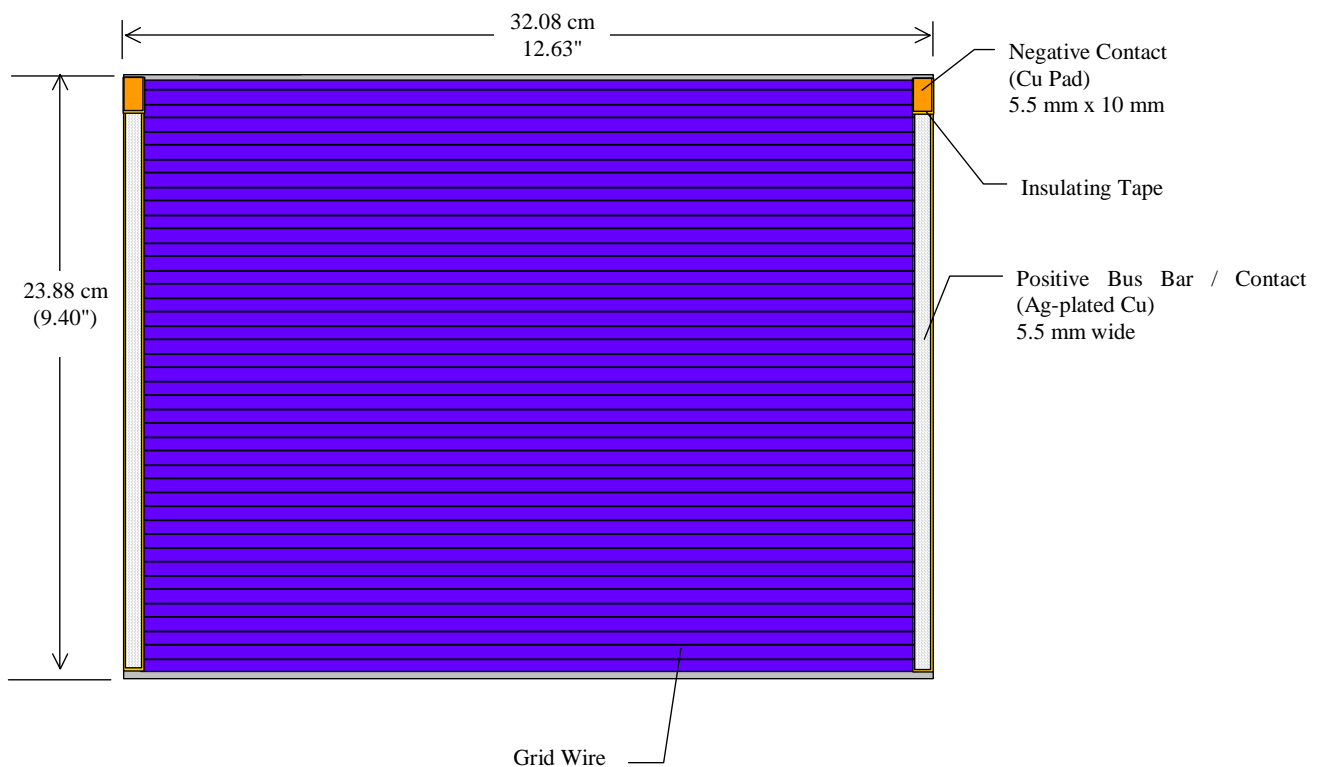


Figure 5. Diagram of a production-size cell on polymer showing the location of contacts and the wire grid.

APPROACHES FOR SPACE CELLS

To supply cells for space and stratospheric use, three approaches are being pursued. The first approach consists of cells on ~1 mil thick stainless steel with a wire grid and bus bars similar to United Solar's terrestrial design, but with spectral response matched to AM0 and a thinner substrate. Also, the encapsulation used for terrestrial products is replaced with much lighter coatings. The second approach is similar, but the cells are deposited on 1 mil thick polymer. These cells have efficiency similar to the cells on steel, but are much lighter, resulting in significantly higher specific power. The third approach is a longer-term effort to make monolithically integrated modules on polymer substrate using laser processes. These cells, without the need for the wire grid, are lighter yet. The current status of the first two approaches is described below.

CELLS ON THIN STAINLESS STEEL

United Solar's terrestrial products are all deposited onto rolls of stainless steel with thickness of 5 mil. To address the space market, the first approach is to leverage our existing experience of making cells on stainless steel by adapting them for space use. To avoid complexity and reduce cost, minimum changes from the established terrestrial cell production processes are made. To optimize the cells for space use, the Al/ZnO back reflector was replaced by a more reflective Ag/ZnO back reflector, and the thicknesses of the component cells were re-optimized to match the triple-junction cell response to the AM0 spectrum. To substantially reduce weight, the stainless steel substrate is thinned down to 0.5 to 1 mil, and the terrestrial encapsulation is replaced by thin, space-compatible coatings. We have previously reported that a total area beginning of life (BOL) efficiency of 12% was measured by NASA Lewis Research Center on a cell with 0.266 cm² total area (1), 10.8% for a cell with 11 cm² area, and 9.5 % for large area cell with 460 cm² area (5). Each of these cells was made in R&D batch systems on stainless steel substrates. Since the 5MW roll-to-roll machines have been devoted to development of cells for space use, significant progress has been made in the performance of cells from the roll-to-roll machines, with performance matching the earlier large area result from the R&D batch machine.

Throughout the development program, we have fabricated large area cells using the roll-to-roll machines for deposition of all the thin film layers at production speeds. The cells have the standard wires and bus bars that are used for the space product. Table 2 shows the BOL 25 °C AM0 I-V parameters for recently made cells (H-strips) measured at NASA GRC under their LAPSS. The aperture area efficiency of the cells is as high as 9.55% (total area efficiency 8.8%).

Table 2. NASA GRC AM0 I-V characteristics (BOL 25 °C) of large area cells on 5mil stainless steel substrate made using roll-to-roll deposition.

Cell # 5MW1944	Top Coating	Aperture Area (cm ²)	V _{oc} (V)	I _{sc} (A)	V _{mp} (V)	I _{mp} (A)	P _{max} (W)	FF	Aperture Area Eff (%)
65D	Bare	130.4	2.279	1.135	1.742	0.977	1.702	0.658	9.55
67D	Bare	130.4	2.278	1.130	1.744	0.966	1.685	0.655	9.45
63C	Bare	130.4	2.272	1.142	1.740	0.977	1.701	0.656	9.54
65C	Bare	130.4	2.273	1.148	1.740	0.972	1.692	0.648	9.49
64E	Bare	130.4	2.285	1.146	1.755	0.960	1.684	0.643	9.45
70D	Bare	130.4	2.288	1.140	1.741	0.960	1.671	0.641	9.38
68E	Bare	130.4	2.286	1.143	1.731	0.957	1.656	0.634	9.29
62B	Bare	130.4	2.285	1.145	1.751	0.958	1.676	0.641	9.40

L-strips, with aperture area 806.5 cm², were also made from material deposited in the roll-to-roll machines at production speeds and measured at NASA GRC under the LAPSS. The cells have a proprietary United Solar top coating to provide environmental protection and increase emissivity. A picture of one of these cells is shown in Figure 6. The I-V curve from the LAPSS measurement of cell 5MW1953-901 at 25 °C is plotted in Fig 7. The total area efficiency of the cell is 9.0%, and the aperture area efficiency is 9.48%.



Figure 6. An L-strip with 806.5 cm² aperture area on ~ 1 mil stainless steel.

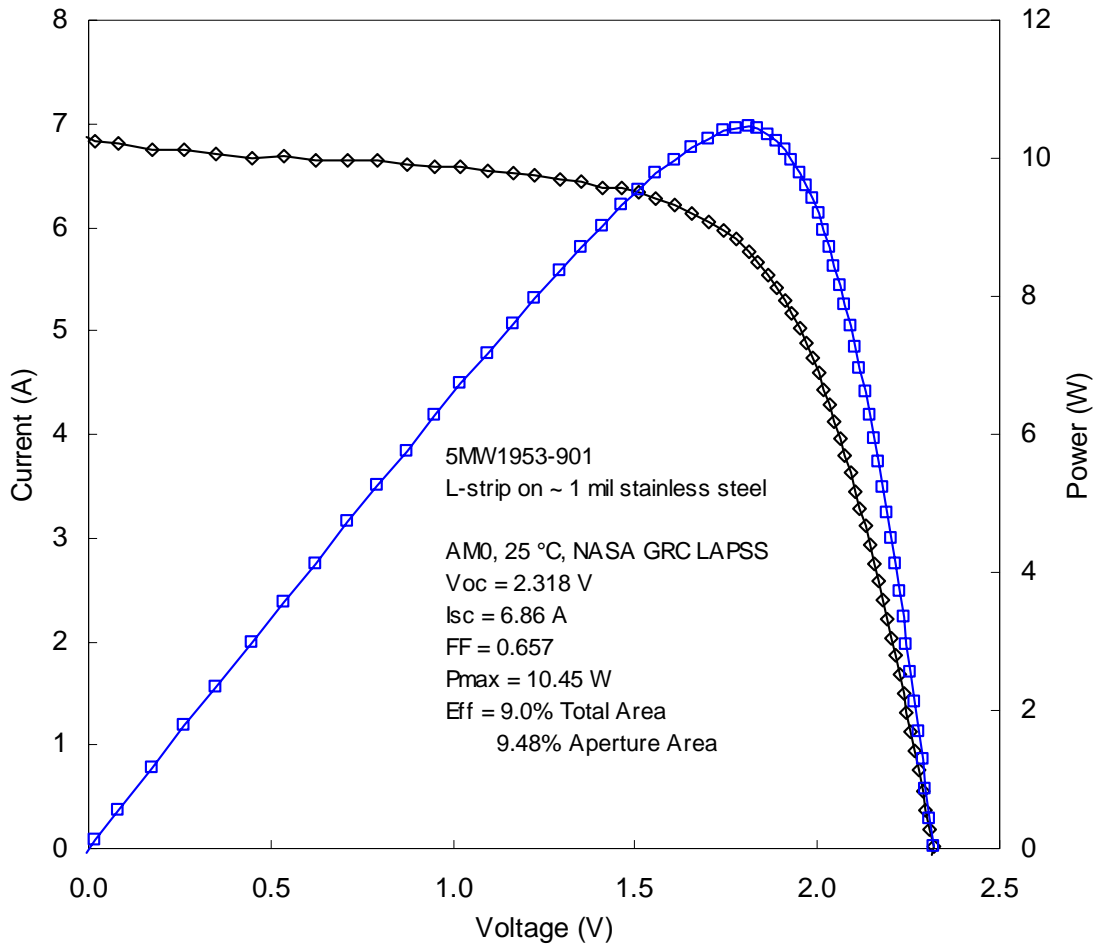


Figure 7. The I-V curve measured at NASA GRC on the LAPSS for an L-strip on ~1 mil stainless steel.

The above results show the current status of the AM0 efficiency of solar cells made on stainless steel substrate in the roll-to-roll machines. Considerable progress has been made in improving the efficiency of large area cells from the roll-to-roll machines since they moved from production of terrestrial cells to development of space cells. Table 3 shows the status of BOL 25 °C efficiency of large area cells measured under the NASA GRC LAPSS solar simulator as a function of time. Before the onset of the program, the status of BOL aperture area efficiency was 8.42%. During the course of the program, we have made an improvement of ~13% and attained a value of 9.55% for H-strips with 130.4 cm² aperture area. This represents a significant gain. Even the largest production cells, with 806.5 cm² aperture area, have demonstrated aperture area efficiency of 9.48% (9.0% total area). Efforts are underway to further improve the efficiency.

Table 3. Progress of large-area solar cell BOL 25 °C efficiency made on stainless steel substrate using roll-to-roll deposition, as measured at NASA GRC under their LAPSS solar simulator.

Time	Sample #	Aperture area (cm ²)	Efficiency (%)
Before program	5MW964-1788C	130.4	8.42
July 2004	5MW1877-1287H1	130.4	8.44
March 2005	5MW1928-175D	130.4	8.90
May 2005	5MW1944-65D	130.4	9.55
August 2005	5MW1953-901	806.5	9.48

The specific power of United Solar PV cells on stainless steel foil made in the roll-to-roll machines has been increased from the previous value of ~400 W/kg to > 500 W/kg. In order to achieve the higher specific power, several changes were made to reduce the mass. The cells use improved, lighter-weight positive and negative bus bar designs, and the stainless steel is thinner. There is a thin proprietary United Solar coating on top.

The AM0 I-V parameters for L-cells with specific power > 500 W/kg are shown in Table 4. The I-V measurements were made under the Spire AM1.5 solar simulator at United Solar, and the results have been corrected for spectral mismatch and intensity to determine the expected AM0 parameters. The specific power for these cells ranges from 515 to 554 W/kg. It is noted that these cells were made earlier in the program, and thus have lower efficiency than has been more recently achieved. If the later, improved a-Si recipe that gave > 9.5% AM0 efficiency as measured at NASA for the cells in Table 2 were used for cells with this lighter design, the specific power is expected to be > 550 W/kg (9.5%, 19.02 g), and as high as 610 W/kg (9.5%, 17.11 g). It should be emphasized that these results are for cells made with the production roll-to-roll depositions, and are representative of what can be made in production. Cells on thin stainless steel are available today in kW quantities with specific power in the range of 400-500 W/kg.

Table 4. Extrapolated AM0 IV parameters for L cells on stainless steel foil with specific power > 500 W/kg.

Cell #	Area (cm ²)	Temp (C)	V _{oc} (V)	I _{sc} (A)	V _{mp} (V)	P _{max} (W)	FF	Eff (%)	Mass (g)	Specific Power (W/kg)
5MW1928-355	806.5	26.1	2.24	6.65	1.79	9.48	0.635	8.60	17.11	554
5MW1928-351	806.5	25.9	2.24	6.73	1.80	9.61	0.636	8.73	17.42	552
5MW1928-352	806.5	26.2	2.24	6.77	1.76	9.60	0.633	8.71	18.00	533
5MW1928-356	806.5	26.0	2.24	6.67	1.80	9.68	0.646	8.79	18.45	525
5MW1928-343	806.5	26.1	2.24	6.81	1.75	9.80	0.641	8.90	19.02	515

CELLS ON POLYMER WITH WIRE GRID AND BUS BARS

Previously, we demonstrated a cell made using slow rate R&D batch depositions on free-standing polymer with AM0 efficiency of 9.0% and specific power > 1250 W/kg (5). Since that time, tremendous progress has been made in our ability to produce high-efficiency cells on polymer using high-volume roll-to-roll depositions, and we are currently able to produce cells using roll-to-roll depositions with performance similar to the previous R&D result. Here we present data on three different cell configurations, all made in the roll-to-roll deposition machines.

Table 5 shows the expected BOL, 25 °C, AM0 I-V parameters for a group of cells from the roll-to-roll machines on 1 mil polymer with ~7.6 cm x ~34.0 cm aperture area (256.0 cm²), and a thin United Solar proprietary top coating. I-V measurements were made under the Spire AM1.5 solar simulator at United Solar. The results have been corrected for spectral mismatch and intensity to determine the expected AM0 parameters. These cells have BOL, 25 °C AM0 efficiency of 9.07% to 9.44%, and specific power 1149 W/kg to 1200 W/kg.

Table 5. AM0, 25 °C I-V parameters for cells with ~7.6 cm x ~34.0 cm aperture area on 1 mil polymer substrate with a thin United Solar coating. Parameters are calculated from United Solar Spire AM1.5 I-V measurements with spectral and intensity corrections.

Cell #	Area (cm ²)	Temp (C)	V _{oc} (V)	I _{sc} (A)	V _{mp} (V)	P _{max} (W)	FF	Eff (%)	Mass (g)	Specific Power (W/kg)
5MW1939-150B	256.0	26.5	2.26	2.22	1.82	3.30	0.657	9.44	2.75	1200
5MW1939-152B	256.0	26.2	2.26	2.22	1.86	3.23	0.644	9.25	2.75	1176
5MW1939-151B	256.0	26.6	2.26	2.19	1.82	3.22	0.651	9.20	2.77	1162
5MW1939-153B	256.0	26.2	2.26	2.21	1.80	3.21	0.644	9.17	2.78	1154
5MW1939-139B	256.0	26.2	2.26	2.18	1.80	3.17	0.644	9.07	2.76	1149

The second set of cells made on 1 mil polymer has 5.05 cm x 30.35 cm aperture area (153.3 cm²), and a United Solar top coating. The AM0 I-V characteristics were measured at NASA GRC under the LAPSS at 25 °C, and the resulting AM0 I-V parameters are shown in Table 6. The BOL, 25 °C, AM0 efficiency and specific power of these cells are 8.84% to 9.26% and 996 W/kg to 1032 W/kg, respectively. The specific power of these cells is lower than in Table 5 mainly due to the double-thickness top coating. The I-V curve measured for cell 5MW1939-77BL on the NASA GRC LAPSS is shown in Figure 8.

Table 6. AM0 I-V parameters for cells from roll-to-roll machines on 1 mil polymer with USOC top protective coating, 5.30 cm x 31.75 cm total area, and 5.05 cm x 30.35 cm aperture area. Data were measured at NASA GRC on the LAPSS at 25 °C.

Cell	Aperture Area (cm ²)	V _{oc} (V)	I _{sc} (A)	V _{mp} (V)	I _{mp} (A)	P _{max} (W)	FF	Eff (%)	Mass (g)	Specific Power (W/kg)
5MW1939-77W1	153.3	2.316	1.287	1.775	1.067	1.895	0.636	9.04	1.85	1024
5MW1939-73W1	153.3	2.317	1.280	1.773	1.066	1.889	0.637	9.01	1.83	1032
5MW1939-75W1	153.3	2.312	1.285	1.731	1.070	1.853	0.623	8.84	1.86	996
5MW1939-74W2	153.3	2.317	1.277	1.748	1.078	1.884	0.637	8.99	1.86	1013
5MW1939-74BL	153.3	2.311	1.280	1.772	1.066	1.890	0.639	9.02	1.85	1022
5MW1939-77BL	153.3	2.309	1.283	1.786	1.087	1.941	0.655	9.26	1.88	1032
5MW1939-71BL	153.3	2.307	1.275	1.772	1.067	1.890	0.643	9.02	1.84	1027
5MW1939-72BL	153.3	2.306	1.269	1.771	1.059	1.876	0.641	8.95	1.83	1025

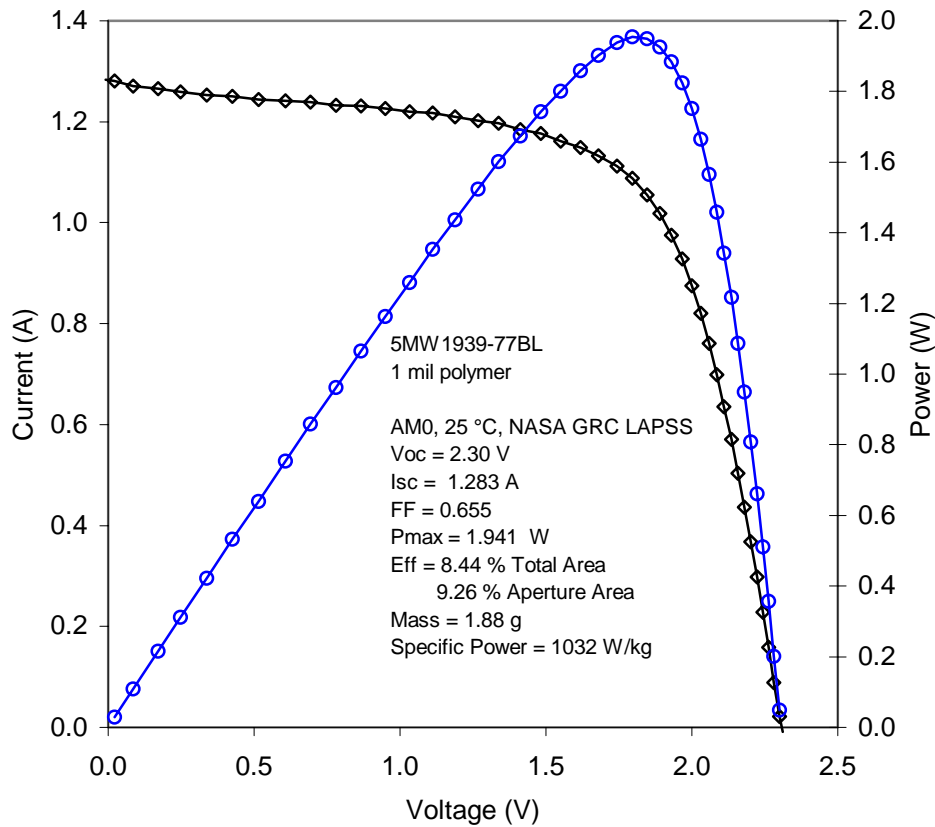


Figure 8. I-V curve for a cell on 1 mil polymer from the roll-to-roll machines as measured at NASA GRC.

Cells with 721.8 cm² aperture area and a thin top coating are also being routinely fabricated. Figure 9 is a picture of one of these cells. The overall dimensions are 23.88 cm x 32.08 cm, which is a total area of 766.1 cm². This is the current production size cell on polymer substrate, and the cells are made from roll-to-roll depositions using fabrication methods that can be used for high-volume manufacturing. The I-V performance of one of the cells as extrapolated from the Spire AM1.5 solar simulator measurement at United Solar is shown in Figure 10. The AM0 curve and parameters are obtained from the AM1.5 measurement by correcting for spectral mismatch and intensity. The BOL, 25 °C AM0 total area efficiency for this cell is 8.7% (9.2% aperture area efficiency) with specific power of 1110 W/kg. These cells thus have similar performance to the smaller cells measured at NASA under the LAPSS. Light-soak testing of cells with a similar recipe has given a derating factor of 0.79 in going from the initial, 25 °C power to that measured at 60 °C after light-stabilization at a stabilization temperature of 60 °C. Application of a derating of 0.79 to the initial values gives a light-stabilized, 60 °C specific power of 875 W/kg for these production cells. This result is obtained for cells from the roll-to-roll machines running at normal production rates, and is thus representative of the performance expected for high-volume production at the present level of optimization. Cells on polymer substrate are presently available in kW quantities with BOL, 25 °C total area efficiency > 8%, and specific power of 750 to 1100 W/kg, depending on the top coating thickness.



Figure 9. A production size cell on 1 mil polymer with total area 23.88 cm x 32.08 cm.

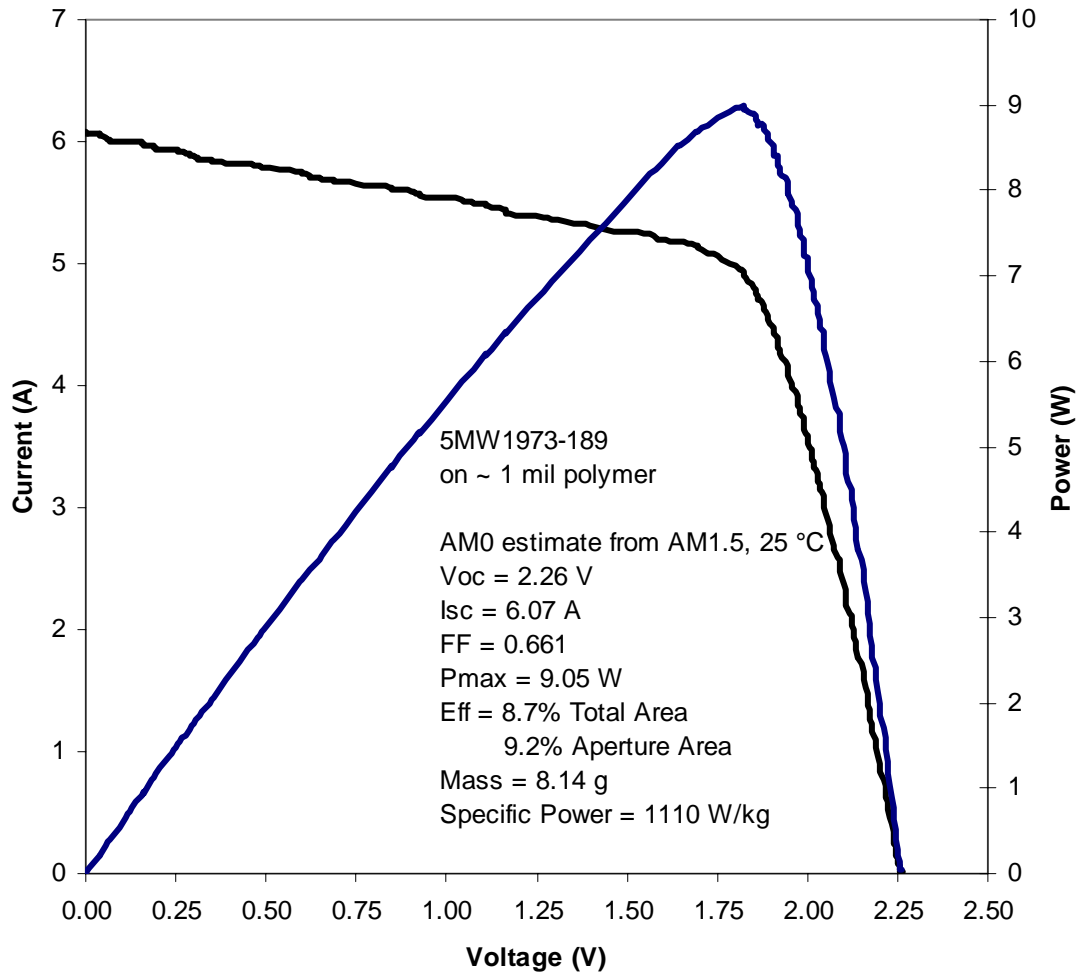


Figure 10. The AM0 I-V curve for a production cell on 1 mil polymer extrapolated from the AM1.5 Spire solar simulator measurement using intensity and spectral mismatch corrections.

The flexible nature of these cells allows for stowage in small volumes, for example, by using a roll-out type of configuration. This is demonstrated in Figure 11, where a series-connected string of production-size cells is shown partially rolled around a tube. Preliminary testing shows that tube diameters of only a couple of inches do not result in damage to the cells on polymer substrate with the United Solar proprietary top coating.

SPACE TESTING

Numerous space-qualification tests have been done and are ongoing with aerospace companies and government laboratories for cells on stainless steel and polymer substrates. Some of the testing that has been done includes LEO and GEO thermal cycling, atomic oxygen, electron and proton irradiation (1), and micrometeorite testing. In addition, the United Solar proprietary top coating has undergone near and vacuum UV and plasma testing. None of these tests has uncovered a problem with the cell design or robustness. In addition, United Solar's a-Si alloy cells have been tested on the MIR space station for 19 months with only minimal degradation (3). Additional flight opportunities are approaching, and more in-space testing results are expected in the coming months.

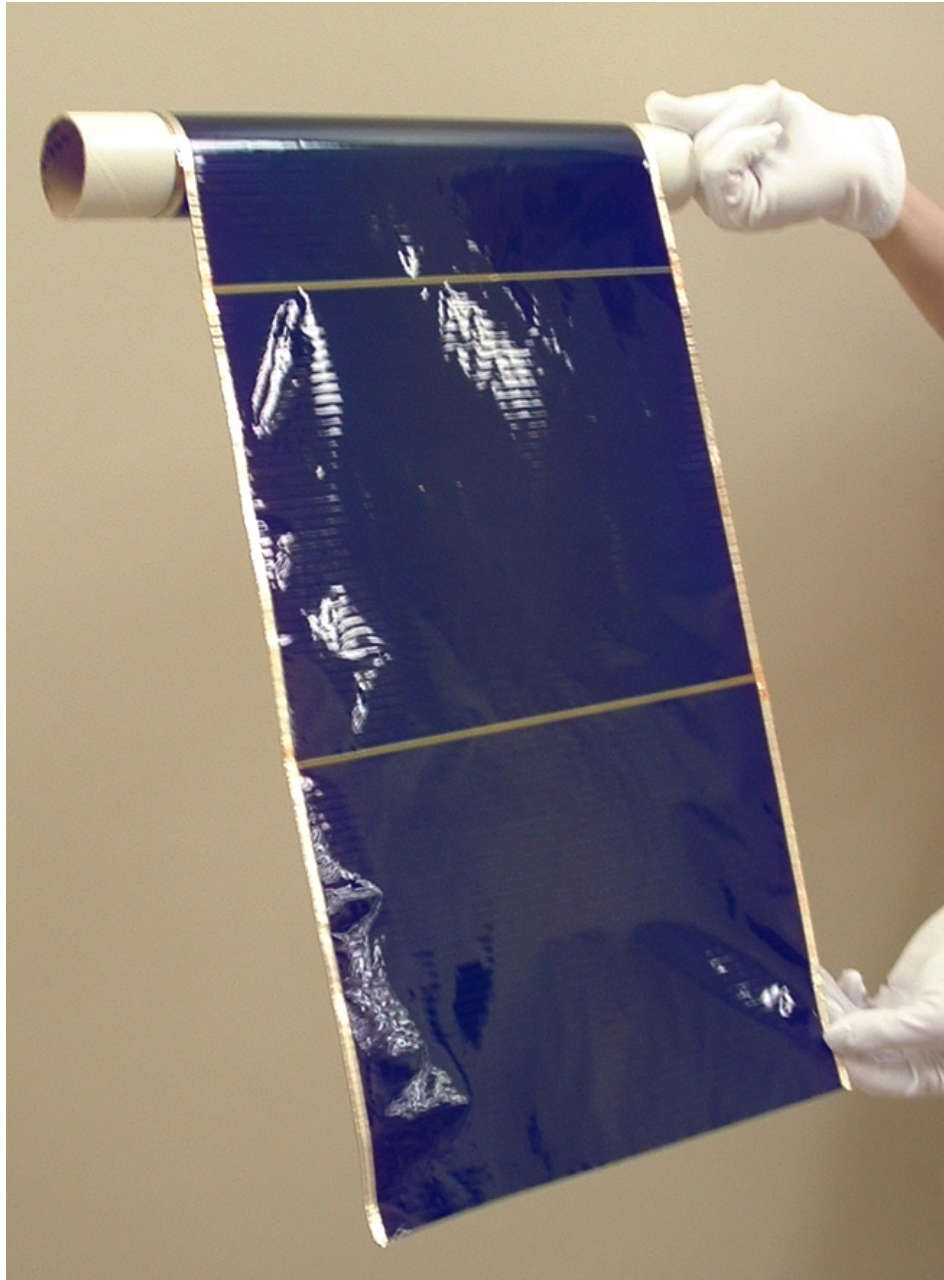


Figure 11. A series-connected string of production-sized cells on 1 mil polymer partially rolled onto a tube.

SUMMARY

United Solar has developed cells for space and stratospheric applications based on a-Si alloy triple-junction cells deposited onto thin stainless steel or polymer substrates. Considerable space-qualification testing has been done, and cells are currently available in kW quantities on thin stainless steel with BOL, 25 °C, AM0 total area efficiency ~9% and specific power of 400 to 500 W/kg. Cells are also available in kW quantities on 1 mil polymer with BOL, 25 °C, AM0 total area efficiency > 8% and specific power 750 to 1100 W/kg depending on the top coating thickness. Monolithically integrated strings of cells on polymer using laser processing are under development.

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